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# The Effect of Climate Change on River Flow and Snow Cover in the NOPEX Area Simulated by a Simple Water Balance Model

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Within the next few decades, changes in global temperature and precipitation patterns may appear, especially at high latitudes. A simple monthly water-balance model of the NOPEX basins was developed and used for the purposes of investigating the effects on water availability of changes in climate. Eleven case study catchments were used together with a number of climate change scenarios. The effects of climate change on average annual runoff depended on the ratio of average annual runoff to average annual precipitation, with the greatest sensitivity in the catchments with lowest runoff coefficients. A 20% increase in annual precipitation resulted in an increase in annual runoff ranging from 31% to 51%. The greatest changes in monthly runoff were in winter (from December to March) whereas the smallest changes were found in summer. The time of the highest spring flow changed from April to March. An increase in temperature by 4°C greatly shortened the time of snow cover and the snow accumulation period. The maximum amount of snow during these short winters diminished by 50% for the NOPEX area even with an assumed increase of total precipitation by 20%.

## Introduction

Global climatic changes caused by increases in the atmospheric concentration of carbon dioxide and other trace gases may begin to appear within the next few decades and could include historically significant increases in temperature, combined with changes in global and regional precipitation patterns. It has been estimated by many authors (see *e.g.* Loaiciga *et al.* 1996) that if 1990-level emissions of

$CO_2$ to the atmosphere remain unabated, its concentration in the atmosphere could nearly double by the year 2100 or thereabouts. Assessments of the consequences of a possible climate change for 'double $CO_2$' ($2\times CO_2$) conditions have become standard. Among the most authoritative climate-change assessments, the IPCC reports (Houghton *et al.* 1990, 1992, 1995) give estimates of temperature increases in the northern hemisphere between 3°C and 5°C, together with precipitation change by as much as 15% under the assumption of a doubling of atmospheric $CO_2$. One of the most important impacts on society of future climatic changes will be changes in regional water availability. Such hydrologic changes will affect nearly every aspect of human well-being, from agricultural productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management. The tremendous importance of water in both society and nature underscores the necessity of understanding how a change in global climate could affect regional water supplies.

In the last decade there has been a number of studies of the potential impact of climatic changes on river flow characteristics and water resources, including the work of Gleick (1986), who reviewed various approaches for evaluating the regional hydrologic impacts of global climatic changes and presented a series of criteria for choosing among the different methods. He concluded that the use of water-balance models appears to offer significant advantages over other methods in accuracy, flexibility, and ease of use.

More studies of using monthly water-balance models to explore the impact of climatic changes have since been reported. Gleick (1987) used a monthly water-balance model for climatic impact assessment for the Sacramento basin. The results suggest that the application of such models may provide considerably more information on regional hydrologic effects of climatic changes than is currently available. It has been noted by several writers (*e.g.* Schaake and Liu 1989; Arnell 1992) that the sensitivity of annual runoff to changes in climatic characteristics is determined by the runoff coefficient in such a way that, the lower the runoff coefficient, the more sensitive the average annual runoff at a given percentage change in climatic characteristics. Present knowledge about likely climatic change has also shown that the largest influences can be expected at high latitudes and during winter time (*e.g.* Houghton *et al.* 1990, 1992, 1995). According to one scenario with doubled atmospheric carbon dioxide as input, Vehviläinen and Lohvansuu (1991) showed that the temperature increase in Finland may be 2-6°C, the precipitation increase 10-30 mm per month and evaporation increase 5-30 mm per month. These climatic changes would result in the increase of mean runoff by 20-50%. Braun *et al.* (1994) examined the hydrological consequences of climatic change for the Romanche River basin (French Alps, area = $224 km^2$, 12.5% glaciers). They found that an increase in air temperature by 2°C would result in an increase of annual discharge by 200 mm/y from the present level of 1,050 mm/y, primarily caused by increased glacier runoff. The research described here presents part of a larger investigation into the implications of climatic variability and change for river flow regimes in the NOPEX area. The boreal forest zone has several characteristics that differ from other regions of the world and which make studies of it imperative in the global context (Thomas and Rowntree 1992; Halldin *et al.* 1995). The current study used a simple monthly water-balance model developed for the Nordic region (Xu *et al.* 1996) with a number of scenarios of change in monthly precipitation and temperature to estimate changes in monthly river flow regimes and snow cover in the NOPEX region.

## Model, Data and Scenarios

### Methodology

The basic method for estimating the impacts of climate change on hydrological behaviour, as implemented in a number of studies (*e.g.* Arnell 1992), has the following stages: 1) determine the parameters of a hydrological model in the study catchment, using current climatic inputs and observed river flows for model validation; 2) perturb the historical time series of climatic data according to some climate change scenarios; 3) simulate the hydrological characteristics of the catchment under the perturbed climate, using the calibrated hydrological model; and 4) compare the model simulations of the current and possible future hydrological characteristics.

Two fundamental assumptions of this paper are that the water-balance model designed to evaluate the impacts of climatic changes on runoff will be able to 1) reproduce reasonably well the historical streamflow record and 2) simulate the streamflow under climatic conditions that are different from the conditions for which the model has been calibrated. In other words, the parameters of the model must not simply reflect the current relationship between climate and hydrological response but also those under a changed climate. The first assumption concerning the ability of the model in reproducing the historical streamflow record has been validated in the study of Xu *et al.* (1996). The second is a strong assumption behind the whole analysis, namely that the model parameters can be used for a changed climate. Strictly speaking, the validation of this assumption is not possible until a climate change has actually occurred and the "experiment is done". Nevertheless, this is a widely used fundamental assumption in the literature (*e.g.* Gleick 1987; Arnell 1992).

### The Model and the Study Catchments

Both model concept and test catchments are discussed in detail by Xu *et al.* (1996). A brief description of the model is given below and in Table 1. The model requires as inputs monthly values of areal precipitation, long-term average potential evapotranspiration and air temperature. The model outputs are river flow and other water-balance components, such as actual evapotranspiration, slow and fast components of river flow, soil-moisture storage, accumulation of snowpack, etc. The model works

Table 1 –Summary of the principal equations of the monthly water-balance model

| | | |
|---|---|---|
| Snowfall: | $s_t = p_t \left\{ 1 - e^{[(c_t - a_1)/(a_1 - a_2)]2} \right\}^+$ | (1) |
| Snowpack: | $sp_t = sp_{t-1} + s_t - m_t$ | (2) |
| Snowmelt: | $m_t = sp_{t-1} \left\{ 1 - e^{-[(c_t - a_2)/(a_1 - a_2)]2} \right\}^+$ | (3) |
| Rainfall: | $r_t = p_t - s_t$ | (4) |
| Potential evapotranspiration: | $ep_t = (1 + a_3(c_t - c_m))ep_m$ | (5) |
| Actual evapotranspiration: | $e_t = \min \left\{ w_t(1 - e^{-a_4 ep_t}),\ ep_t \right\}$ | (6) |
| Baseflow: | $b_t = a_5\, sm^+_{t-1}$ | (7) |
| Fast flow: | $f_t = a_6\, sm^+_{t-1}\,(m_t + n_t)$ | (8) |
| Total runoff: | $d_t = b_t + f_t$ | (9) |
| Water balance equation: | $sm_t = sm_{t-1} + r_t + m_t - e_t - d_t$ | (10) |

where: $w_t = r_t + sm^+_{t-1}$ is the available water; $\mathrm{sm}^+_{t-1} = max(sm_{t-1}, 0)$ is the available storage; $n_t = r_t - ep_t(1 - e^{-r_t/ep_t})$ is the active rainfall; $p_t$ and $c_t$ are monthly precipitation and air temperature, respectively; $ep_m$ and $c_m$ are long-term monthly average potential evapotranspiration and air temperature, respectively; $a_i$ (i = 1, 2, ..., 6) are model parameters.

Table 2 – Characteristics (1981.9-1991.8) of 11 test catchments in the NOPEX region (1981.9-1991.8)used to assess climate-change impact.

| Station | Abbreviation | River | Area ($\mathrm{km}^2$) | Mean annual precipitation (mm) | Runoff coeff. (%) |
|---|---|---|---|---|---|
| Åkesta Kvarn | AK | Svartån | 730.0 | 733 | 36 |
| Gränvad | GR | Lillån | 168.0 | 726 | 34 |
| Härnevi | HA | Örsundaån | 305.0 | 738 | 39 |
| Lurbo | LU | Hågaån | 124.0 | 750 | 41 |
| Ransta | RA | Sävaån | 198.0 | 734 | 37 |
| Sävja | SA | Sävjaån | 727.0 | 732 | 33 |
| Sörsätra | SO | Sagån | 612.0 | 729 | 45 |
| Stabby | ST | Satbbybäcken | 6.6 | 693 | 34 |
| Tärnsjö | TA | Stalbobäcken | 14.0 | 733 | 36 |
| Ulva Kvarn | UL | Fyrisån | 950.0 | 755 | 32 |
| Vattholma | VA | Vattholmaån | 284.0 | 750 | 36 |

as follows: precipitation $p_t$ is first split into rainfall $r_t$ and snowfall $s_t$ by using a temperature-index function, snowfall is added to the snowpack $sp_t$ (the first storage) at the end of the month. Snowmelt is calculated by a temperature-index method. Before the rainfall contributes to the soil storage as "active" rainfall, a small part is subtracted and added to evapotranspiration loss. The soil storage contributes to evapotranspiration $e_t$, to a fast component of flow $f_t$ and to base flow $b_t$.

Observed precipitation, runoff and land-use data were available for 11 catchments located within or close to the NOPEX area (Table 2). Eleven years (1981-91) of monthly precipitation, air temperature and runoff data were used in the study to calibrate the model parameters.

### The Changes of Climatic Variables

Scenarios for changes in temperature and precipitation differ considerably between different impact studies. Moreover, annual changes are distributed during the year by various methods. Some authors (*e.g.* Nemec and Schaake1982; Ng and Marsalek 1992) assume constant distributions of climatic changes and multiply historical precipitation records by constant factors and adjusted historical temperatures by constant increments. In this study, two temperature scenarios, TC1 with the increases of 1°C and TC2 with the increases of 4°C, were used. The precipitation for each month was increased with 10% (denoted as PC1) and 20% (denoted as PC2) of the mean precipitation for the same month, respectively such that the precipitation in dry months increased by a smaller amount in absolute terms than in wet months.

A total of 8 scenarious were considered in this study. The 4 already mentioned (TC1, TC2, PC1, PC2) were first studied in isolation. Another 4 were then made up as combinations of the first four (PC1+TC1, PC1+TC2, PC2+TC1, PC2+TC2).

## Results and Discussion

### The Change of Average Annual Runoff

The average annual discharge for the NOPEX area increased by 18.6% and 39.3% when precipitation increased by 10% and 20%, respectively (Table 3). The increases of temperature by 1°C and 4°C decreased the annual discharge by 4.3% and 13.4%, respectively. It was of interest to examine the impact of combined changes in precipitation and temperature on streamflow. As far as the mean annual runoff was concerned, the smallest changes were found under the scenario PC1+TC2, where the 10% increase of precipitation mainly contributed to the increment of evapotranspiration caused by the higher temperature.

Several earlier modelling studies (*e.g.* Schaake and Liu 1989; Arnell 1992) indicate that the sensitivity of annual runoff to changes in precipitation is determined by the runoff coefficient in such a way that arid places will be much more affected than humid and low flows more than high. Schaake and Liu (1989) found that, in the

Table 3 – Changes of simulated mean annual runoff under different scenarios

| Basin | Runoff | Changes of annual runoff under different scenarios (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coeff. | PC1 | PC2 | TC1 | TC2 | PC1+TC1 | PC1+TC2 | PC2+TC1 | PC2+TC2 |
| AK | .36 | 18.7 | 40.0 | -6.5 | -18.1 | 10.0 | -4.9 | 28.4 | 9.6 |
| GR | .34 | 20.1 | 43.0 | -3.4 | -10.9 | 15.2 | 5.1 | 35.9 | 22.8 |
| HA | .39 | 17.5 | 36.3 | -3.3 | -11.0 | 12.8 | 3.4 | 30.6 | 18.7 |
| LU | .41 | 16.1 | 33.3 | -3.7 | -13.3 | 11.3 | 0.07 | 27.3 | 14.2 |
| RA | .37 | 17.8 | 36.8 | -4.1 | -13.3 | 12.3 | 1.1 | 30.2 | 16.4 |
| SA | .33 | 20.0 | 44.0 | -4.4 | -13.6 | 13.3 | 1.4 | 33.4 | 17.3 |
| SO | .45 | 15.1 | 31.0 | -8.1 | -23.1 | 5.6 | -11.7 | 19.8 | 0.36 |
| ST | .34 | 18.6 | 38.9 | -4.5 | -15.3 | 12.7 | -0.20 | 31.3 | 16.1 |
| TA | .36 | 18.1 | 38.3 | -5.6 | -16.6 | 10.3 | -3.7 | 28.4 | 10.3 |
| UL | .32 | 24.6 | 51.4 | -1.6 | -6.1 | 20.2 | 11.9 | 46.8 | 33.2 |
| VA | .36 | 18.5 | 39.5 | -2.2 | -6.5 | 14.5 | 8.0 | 33.3 | 23.4 |
| MEAN | .37 | 18.6 | 39.3 | -4.3 | -13.4 | 12.6 | 0.96 | 31.4 | 16.6 |

south-eastern US, a 10% change in precipitation might produce between 20% and 45% changes in mean annual runoff for humid and arid areas, respectively. Arnell (1992) shows, for British catchments, that a 20% increase in average annual rainfall may give an increase in average annual runoff ranging from 26% to 58%. The largest increases occur when the runoff coefficient is lowest. The results produced in this study for the precipitation increase show similar impacts (Fig. 1). It is seen that a 10% increase in average annual precipitation gave an increase in average annual runoff ranging from 15% (with runoff coefficient equal to 0.45) to 25% (with runoff coefficient equal to 0.32) while a 20% increase in average annual precipitation gave an increase in average annual runoff ranging from 31% to 51% with the largest increases for the lowest values of the runoff coefficient. These scenarios should not necessarily be seen as the most likely future climates in the region: they are primarily designed to show the sensitivity to change within a reasonable interval.

## The Change of Average Monthly Runoff

Changes in monthly and seasonal runoff volumes are as important to water resource managers as changes in annual totals, and these changes will be controlled by catchment geology, soils and vegetation as well as by climate. Changes in average runoff in each month for catchment Fyrisån at Ulva Kvarn under scenario PC2+TC2 (temperature increases by 4°C and precipitation increases by 20%) were used as examples (Fig. 2).

It is seen that the greatest changes in monthly runoff were in winter (from December to March) while the smallest were found in summer. Increased summer precipitation was counterbalanced by an increase of evapotranspiration (Fig. 3) caused by the increase in temperature. The spring-time high flows (as measured in April) de-

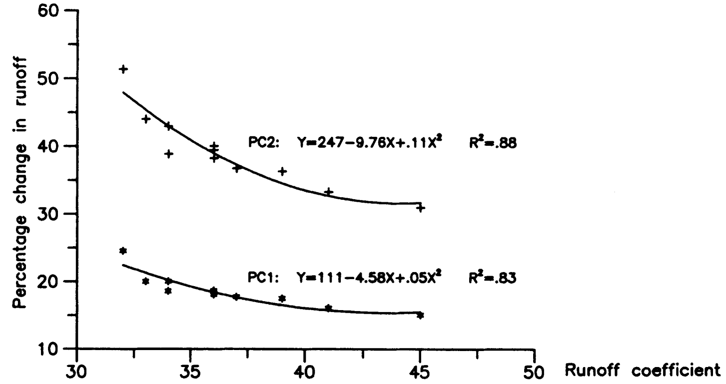

Fig. 1. Changes in average annual runoff under scenarios PC1 (+10% precipitation) and PC2 (+20% precipitation).

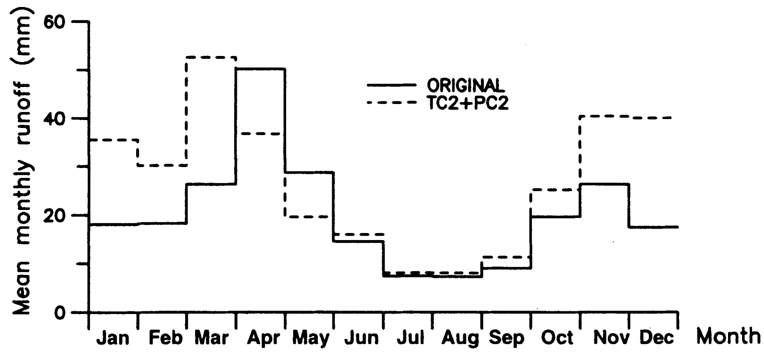

Fig. 2. Monthly mean runoff with original data (1981.9-1991.8) and under scenario TC2+ PC2 (+4°C and +20% precipitation) for the Fyrisån river catchment at Ulva kvarn.

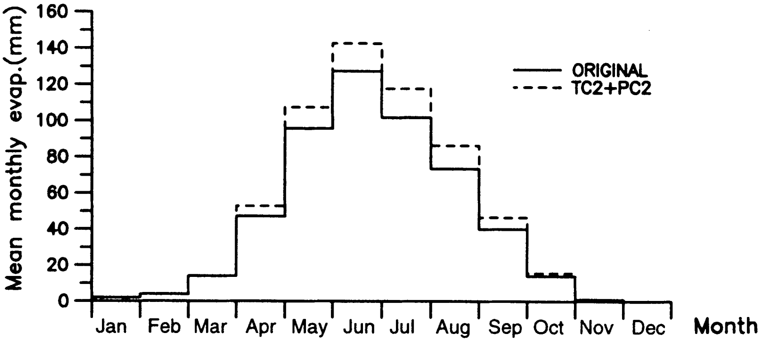

Fig. 3. Monthly mean evapotranspiration with original data (1981.9-1991.8) and under scenario TC2+ PC2 (+4°C and +20% precipitation) for the Fyrisån river catchment at Ulva kvarn.

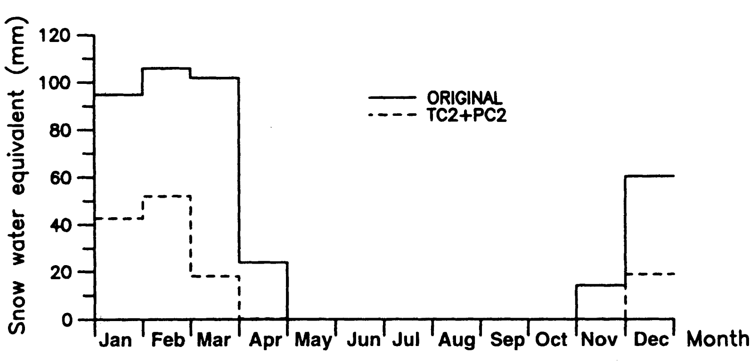

Fig. 4. Monthly mean areal snow water equivalent storage with original data (1981.9-1991.8) and under scenario TC2+ PC2 (+4°C and +20% precipitation) for the Fyrisån river catchment at Ulva kvarn.

creased considerably because of the smaller snow storage in the spring (Fig. 4), and the time of the highest flow changed from April to March. These findings are well supported by the results of Vehviläinen and Lohvansuu (1991) and Ng and Marsalek (1992) showing that the climatic input changes may lead to a significant redistribution of the annual streamflow, with the largest increase of runoff in winters.

## The Change of Snow Cover

Again, the changes under scenario PC2+TC2 are used as examples in the discussion. The increase in temperature by 4°C greatly shortens the time of snow cover and the snow accumulation period (Fig. 4). Also the maximum amount of snow during these

Table 4 - Maximum monthly snow water equivalent simulated with original data (1981.9-1991.8) and under scenario PC2+TC2.

| Catchment | Area (km2) | Original data (mm) | PC2+TC2 (mm) | Changes (%) |
|---|---|---|---|---|
| AK | 730.0 | 110.6 | 53.3 | -51.8 |
| GR | 168.0 | 81.5 | 41.3 | -49.3 |
| HA | 305.0 | 96.6 | 49.4 | -48.8 |
| LU | 124.0 | 84.5 | 43.2 | -48.9 |
| RA | 198.0 | 93.8 | 46.8 | -50.2 |
| SA | 727.0 | 85.2 | 42.0 | -50.7 |
| SO | 612.0 | 90.4 | 45.4 | -49.8 |
| ST | 6.6 | 73.5 | 35.8 | -51.2 |
| TA | 14.0 | 111.0 | 55.7 | -49.9 |
| UL | 950.0 | 106.0 | 52.0 | -50.9 |
| VA | 284.0 | 120.0 | 59.2 | -50.6 |
| MEAN |  | 95.7 | 47.6 | -50.2 |

short winters was diminished by 51% even with the proposed increase of total precipitation by 20% (Table 4). The results are in concordance with the findings of Vehviläinen and Lohvansuu (1991). They found that an increase in temperature by 5-6°C in winter greatly shortened the time of snow cover and the snow accumulation period. Also the maximum amount of snow during these short winters was diminished by 80% in southern and central Finland and by 50% in northern Finland even with a 10-15% increase in winter precipitation.

## Conclusions

A monthly water-balance model was used in this study to show the impact of given scenarios of climate changes on river flow regimes and snow cover in the NOPEX area.

The effect of a given climate change scenario on average annual runoff seems to be determined largely by the current ratio of average annual runoff to average annual precipitation. In the NOPEX area, a 20% increase in annual precipitation would result in an increase in average annual runoff ranging from 31% to 51%. The largest increases would occur when the runoff coefficient is lowest. The annual streamflow is less affected by changes in temperature alone. Reductions of up to 4.3% and 13.4% were found as a result of temperature increases of 1°C and 4°C. The smallest changes in annual streamflow were found under the scenario PC1+TC2, where the 10% increase of precipitation mainly contributed to the increment of evapotranspiration because of the higher temperature (increase by 4°C).

At the monthly scale, the climatic input changes led to a significant redistribution of the streamflow within a year. The changes caused by scenario PC2+TC2 (temperature increases by 4°C and precipitation increases by 20%), for example, showed a strong increase in discharges over the whole winter period and especially at the beginning and at the end of the winter. The increase of evapotranspiration counterbalanced the effect of a precipitation increase during summer and the change in discharge was smallest in summer.

The most prominent effect of climate change on snow cover, as exemplified by scenario PC2+TC2, was the shortening of winters and snow accumulation periods. This caused a strong increase in discharge over the winter period and a change of the time of the highest spring flow from April to March. The maximum amount of snow during these short winters was diminished by 50% for the NOPEX area.

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